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An Eye Tracking System for Analysis of Pilots' Scan Paths

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Portable eye movement and automated analysis systems have been developed for use in pilot training and other applications where it is necessary to monitor and analyze changes in an observer's point of regard. The eye movement system hardware consists of a lightweight, head-mounted, two-dimensional eye tracker and miniature scene camera, an electronic control and processing unit, and a video recorder and monitor. This system, manufactured by El Mar, Inc., is easily transportable and weighs less than 10 Kg. During training, a small crosshair indicating the point of regard is electronically combined with video from the scene camera and both are recorded on video tape for later analysis by an integrated image processing system. The automated analysis system determines which objects were viewed, how long each was viewed, and the order in which they were viewed. The present systems were used to measure and analyze the visual scan paths of pilots in three aircraft simulators. This was done to determine whether data of this kind can be used to increase training effectiveness by identifying efficient scanning strategies and by quantifying differences in the behavior of expert and novice pilots. Scan paths were evaluated for: (a) T-37 instructor pilots (IPs) and T-37 student IPs (rated pilots training to be IPs) while they performed precision instrument approaches in a motion base simulator, (b) F-16 IPs while performing air-to-air scenarios in the Air Combat Engagement Simulator (ACES) and (c) F-16 LANTIRN IPs while performing low-level scenarios in the LANTIRN simulator. The results of these evaluations are described.

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PREFACE

This report documents an experiment using an eye tracking system to analyze pilots' scan paths. This research was conducted under Work Unit 1123-B2-06, Aircrew Training Research Support; Contract F41624-95-C-5011 with Hughes Training, Inc-Training Operations. The Principal Investigator was Dr Byron J. Pierce; the Laboratory Contract Monitor was Mr Daniel Mudd.

This effort is part of an Armstrong Laboratory, Human Resources Directorate, Aircrew Training Research (AL/HRA) program to provide behavioral research support for the Air Force's Warfighter Training Effectiveness Behavioral Research which includes eye tracking technology for aircrew training.

An Eye Tracking System for Analysis of Pilots' Scan Paths

INTRODUCTION

Since the early 1900s, a variety of objective methods have been developed for the purpose of measuring eye position. These devices have been instrumental in evaluating basic motor and neurological aspects of the oculomotor control system, as well as in providing diagnostic information for medical and clinical evaluations. Numerous behavioral and human factors studies have been conducted using these eye-tracking technologies to measure eye position. Information gathered using these systems has been integral in determining field-of-view (FOV) requirements in simulators (Dixon, Rojas, Krueger, & Simcik, 1990), and in controlling high resolution area-of-interest display systems (Wetzel, Thomas, & Williams, 1990). The predecessor of the current portable system described herein was used to assist in the evaluation of situational awareness and as a post-mission debriefing tool in an F-15 simulator at Armstrong Laboratory's Aircrew Training Research Division, in Mesa, AZ, using mission-ready F-15 pilots. This system used a small video camera and an eye tracker attached to a helmet worn by the pilot. An electronic cursor corresponding to eye position was then generated and combined with video from the scene camera. Using this system, we were able to accurately determine the pilots' line of sight (direction of gaze) to any instrument in the cockpit. In addition, we were also able to confirm visual contact with out-of-the-cockpit objects. These data, along with all cockpit communications, were then recorded onto video tape for manual analysis. In the debriefing sessions subject-matter experts were, on occasion, able to determine and show the pilot occurrences of missed cues or other events that led to reduced pilot situational awareness, and in some cases, reduced mission effectiveness. Manual analysis of the video tapes allowed us to determine the scan path sequence, dwell time, frequency of instrument usage, and overall situational awareness from selected pilots.

In the training environment, eye tracking can be used to differentiate and objectively describe visual behavior differences between "expert" and "novice", or less skilled, pilots or system operators revealing effective training techniques and/or eye movement behavior that may be difficult to verbally describe, otherwise observe, or diagnose by others. Further, line-of-sight information can also be used to provide feed-back to the user with respect to scanning technique, detection of scan breakdown, and as a teaching and diagnostic tool for improving training by showing effective eye movement behavior.

In this report, we describe the development of a lightweight, easy-to-use, portable eye position measurement system and a companion automated analysis system. We also discuss several training related applications for which the portable system has been used. To date, this system has been used with T-37 instructor pilots (IPs), T-37 student IPs (rated pilots training to be IPs), and F-16 IPs in three aircraft simulators: (a) The T-37 motion base simulator at Randolph AFB, TX; (b) The F-16 Air Combat Engagement Simulator (ACES) (formerly the Simulator for Air-to-Air Combat, or SAAC) at Luke AFB, AZ; and (c) The F-16 LANTIRN simulator, also located at Luke AFB.

A Basis For Eye Movements

We move our eyes primarily to extract information from the visual environment and to stabilize images on the retina during free head movement. Our eyes also move to compensate for changes in head position and orientation as sensed by the vestibular system. The vestibular system is also responsible for changing eye position based on gravitational and accelerative input forces. Because the world is perceived as stable and visually clear throughout the visual field, we are often unaware of our own eye movements or of the integrating processes that occur. Nevertheless, eye movements and scanning patterns are indicators of thought and mental processing involved during visual information extraction.

We move our eyes almost constantly, extracting information from the visual world. Due to organization of the eye, specifically, the retina, the clarity with which we see an object and the extent to which it is resolved is dependent on the position of our eyes with respect to the object of interest. Our

ability to see color and fine detail is limited to a very small centrally located area on the retina called the fovea which is roughly 1.5 millimeters in diameter. Consequently, one of the basic functions of the eye movement control system is to position and stabilize the eyes such that the projected image of an object falls on the fovea, allowing maximum extraction of visual information concerning that object. An example of head and eye movement occurring during visual scanning is shown in Figure 1.

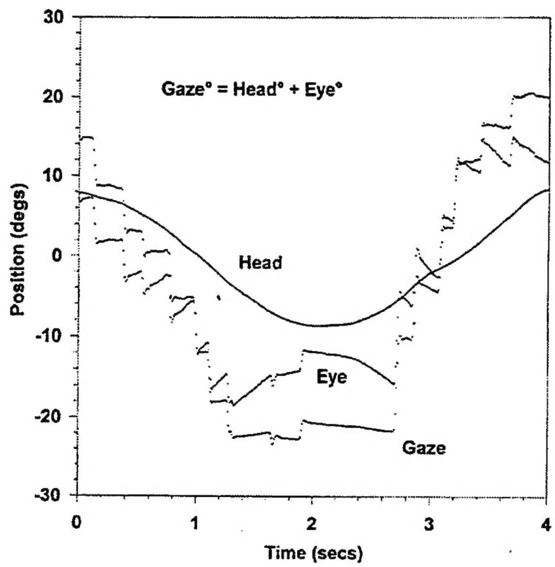

Figure 1. Examples of Saccadic, Compensatory Smooth Eye Movement and Head Movement During Visual Scanning. For clarity, only the horizontal component of head and eye movement and resulting gaze are shown. The sum of head and eye position is equal to the line of sight or gaze position. Stabilized gaze results from the eyes moving at roughly equal rate but opposite in direction to that of head during the stabilized fixation period.

Fast eye movements called saccades, occur during visual search, while reading, or when performing instrument cross-checks. Saccades are volitional and during the ballistic portion, the eyes can reach peak velocities in excess of 400°/s, reaching peak accelerations in excess of 30,000°/s^2, all in under 50 ms. Between saccadic movements, the eyes pause and fixate for at least 200 ms. We can voluntarily change our eye position no more than 4 to 5 times per second. We can accurately position our eyes on a target within a couple tenths of a degree from the retinal fovea. During the pause when the object is stabilized on the fovea, the maximum amount of visual information about the object or target is extracted. Free head movement during visual search, as shown in Figure 1, allows the eyes to move at roughly equal velocity but opposite direction to that of the head which stabilizes an image on the retina. If the head is stationary and a target moves smoothly, the eyes will rotate at roughly the velocity of the target. Generally, smooth eye movement is involuntary; we cannot move our eyes smoothly in the absence of a target. If the target and eye velocities match, in effect, the eye has stabilized on the target, and the fine details of the target can be realized. This eye movement system is best at tracking smoothly moving targets whose velocities are often less than 30°/s. Errors in tracking in excess of a few tenths of a degree are often corrected by saccades which rapidly reposition the eye back on the target. If the movement of an object is smooth, but at a higher velocity, the ability to maintain smooth eye movement diminishes.

THE PORTABLE EYE MEASUREMENT SYSTEM

The ability to measure eye position provides a tool for knowing the look point of that person. Most people, however, are not always consciously aware of where their eyes are looking at any given instant of time.

The measurement of eye position, therefore, provides a detailed record and history of visual behavior and scanning patterns over time.

A number of devices and techniques have been developed, such as electro-oculography, magnetic search coil systems, photoreflective methods, imaging systems, and video-based image devices to obtain accurate measurements of eye position. Due to the nature of these types of devices and their limitations, most have been restricted to use in the laboratory. Fewer systems have been specifically developed for non-laboratory or "non-stationary" conditions and are able to provide accurate information for various applications. These systems track a combination of an estimate of the pupil center and corneal reflections to account for helmet slippage in a dynamic environment. Still, major limitations of systems used in simulator/eye- tracking studies include transporting the bulky, yet fragile, system components, difficulty of operation, and the amount of time and labor required to analyze and compile the data. The manual analysis process could often take days to analyze only a few minutes of eye position data.

The positive response from subjects, including the pilots from the F-15 situational awareness test and subsequent off-site tests in a commercial Boeing 757 simulator, encouraged us to pursue development of the current companion systems. The primary goals of this effort have been to reduce the size and weight of the system, while improving overall ease of use, setup time, and accuracy. Further, decreasing the time and effort required to analyze the data was also key. Based on information gathered from pilots, the head-mounted eye tracker and video scene camera were redesigned to increase comfort and reduce visual restrictions. The video-based automated analysis system, described herein, allows rapid quantification of eye movement scan path and other visual information. The system reduces the analysis and data reduction process to almost real time. The portable eye-tracking system and companion automated analysis system have been under development for the past several years in close collaboration with El Mar, Inc. and Armstrong Laboratory in Mesa, AZ.

Features of the Portable Eye Measurement System

The complete portable eye measurement system is shown in Figure 2. The system consists of a main processor unit, a hand controller, an 8 mm VCR with recorder and display, and an adjustable headband supporting the eye tracker sensor and scene camera. The headband also supports a standard military-style adjustable microphone and a pair of miniature earphones.

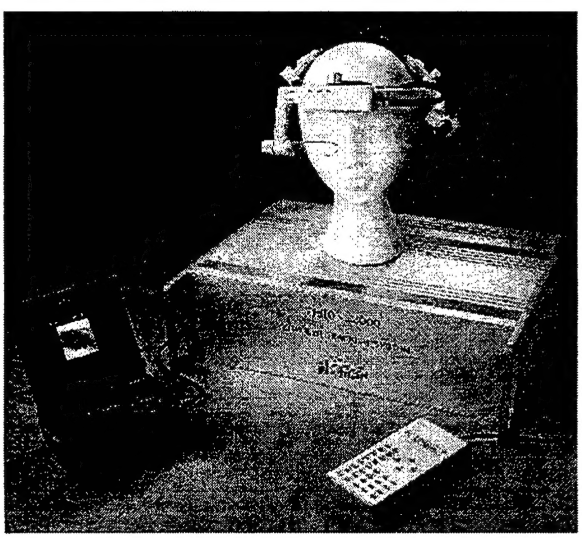

Figure 2. Components of the El Mar, Inc. Vision 2000 Portable Eye Measurement System. From left to right, the 8 mm VCR and display, headband with eye tracker sensor and side-mounted scene camera, the main processor, and hand controller unit.

The weight of the main processing unit is approximately 8 kg. The headband with scene camera and communications system weighs approximately 300 g. The complete system can be transported within a single case.

Principle of Eye Measurement Operation

The system is based on the dark pupil principle. It provides estimates of horizontal and vertical eye position and pupillary size at a rate of 60 Hz.

The system uses an estimate of pupil center and compares this measurement with the positions of two corneal reflections. The virtual images formed by the corneal reflections are the result of two noncollimated infrared light emitting diodes (LEDs) located within the plastic housing above the eye. The infrared LEDs are pulsed at 60 Hz and homogeneously illuminate the eye with less than 300 microwatts/cm^2 of energy. Because the infrared sources and the imaging optics are not coaxial to the eye, the pupil remains dark. A shatterproof plastic beam-splitter located below the line of sight of the right eye redirects the reflected infrared (IR) light from the eye to a two-dimensional charge-coupled device (CCD) array located in the plastic housing above the eye. A set of knobs on the plastic housing allows the user to focus and translate the image of the eye.

Figure 3 exhibits an infrared image of the eye showing the two corneal reflections (two bright dots) and an estimate of the dark pupil center (the crosshair). The system can measure eye movements up to ±45° horizontal (H) and up to ±35° vertical (V). The system has an accuracy of better than ±0.5° for changes in eye position less than ±15° H and V which decreases to ±1° at the limits. The resolution of the system is better than 0.2°. The pupillary corneal difference method also provides a method to distinguish between headband movement and changes in eye position. Without this compensation, changes in headband position of only 1 mm would appear equivalent to an eye movement of up to 10°. With the portable system, translations up to 5 mm can be tolerated.

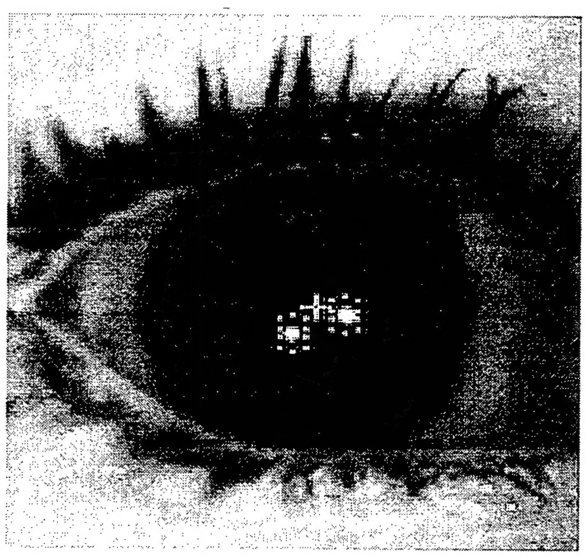

Figure 3. Infrared Image of the Eye Taken from the Portable System, Showing Two Corneal Bright Reflections (Surrounded By Dotted Boxes) and the Pupillary Center Estimate Indicated by the Cross. Eye position is based on the difference between the pupillary center estimate and the positions of the corneal reflections.

The Main Processor Unit.

The main processor unit is a stand-alone device, controlling all functions of the eye-tracking system. The primary control functions include: eye position and pupillary estimation, eye calibration, video display, cursor generation and control, and connections to a VCR and PC. All functions of the main processor unit can be accessed and controlled via the hand-held key pad. Program and eye tracking parameters are stored in electrically erasable programmable ROM. Program updates can be loaded from any DOS-based PC to the main processor unit via one of two serial ports. A serial port can also be used to graphically view actual eye movement data via connection to a PC. Using the hand-held key pad, various system and control parameters can be set for a specific training environment or condition, such as calibration angles, scene camera focal length, and cursor style. Data from the portable system are recorded onto a high fidelity stereo VCR tape recorder. These data include video from the scene camera and cursor, as well as encoded audio data comprising horizontal and vertical eye position, pupillary size, blink and system status information, and frame count. The other audio channel can be used to record voice communications. Eye position data are stored at a rate of 60 Hz. Additional stored data include the recording of event/playback markers, system status, and frame counter information. The hand-held key pad allows the user to mark "significant events" on the video tape for later review without having to search the entire tape.

The hand controller key pad controls the basic functions of the portable system. When preparing to eye track a subject, the key pad is used to select and control various functions of the main processor unit required during the initial adjustment and calibration of the eye measurement system. With the eye tracker headband on the individual, the key pad can be used to switch between an image of the eye, as shown in Figure 3, and imagery from the head-mounted scene camera. If the eye alignment is correct, a button on the key pad can be pressed which initiates a startup procedure, automatically adjusting the infrared LED intensities and contrast for optimal performance based on characteristics of the individual's eye. This process takes less than five seconds. Upon completion of the automated startup process, a message is displayed on the screen confirming the results of the adjustment. The system also allows the user to manually override or adjust the LED intensities and contrast via the key pad should special circumstances or conditions require manual adjustment.

The key pad is used during calibration of the eye measurement system. During calibration, the individual is asked to look at a series of known calibration points placed along the horizontal and vertical axes on a calibration card. At each point, a measurement of eye position is taken by pressing a button on the key pad. At the conclusion of the calibration, a message is sent to the display screen confirming the outcome of the calibration. The scene camera is then aligned with respect to the position of the individual's eye. The key pad is used to properly align the cursor, corresponding to eye position, with respect to the head-mounted scene camera. The key pad may also be used to make minor cursor corrections, if required.

The Recorder and Video Display.

The portable system includes a compact Sony Watchman used for eye and scene alignment, calibration, and for observation of the user's gaze response. Based on our requirements to resolve imagery from the F-16 Head-Up Display (HUD) during playback, we use a Super VHS recorder which offers nearly twice the resolution of a standard VHS recorder. To simplify operator use, the functions of the recorder can be controlled via the hand-held key pad.

The Scene Camera.

A black-and-white scene camera (Elmo Model EM 102-BW) is mounted to the side of the headband support. For most applications, the scene camera is mounted level with the eyes at roughly the same distance to the objects of interest as to that of the eye. When used with aircraft having collimated HUDs, the scene camera must be mounted in the pupillary plane, directly between the eyes to minimize parallax. A variety of interchangeable lenses have been used based on the size of the aircraft instrument panel, the

level of detail required, and scene camera FOV. Presently, we have used lenses with horizontal FOVs of approximately 102°, 90° and 45°. Often, the choice of a lens is determined by balancing the requirements of FOV and detail, considering that as FOV increases, detail decreases.

THE AUTOMATED ANALYSIS SYSTEM

The automated analysis system performs image analysis on each frame of the recorded video, combining these data with eye position coordinate data to determine the line of sight. To date, the system has been used to analyze data collected during research studies conducted with T-37 IPs and T-37 student IPs while performing instrument landings in a T-37 motion base simulator at Randolph AFB.

To determine the line of sight to an object, both head and eye position must be known. A significant advantage of the portable system is that it does not require the use of an external head position measurement system which is often prone to interference from other objects or surrounding obstructions. Instead, we estimate head position based on a set of unique reference markers placed within the FOV of the scene camera.

Using a method similar to triangulation, head position is estimated based on the relationship between a set of fixed reference markers. The reference markers resemble the spokes of a wagon wheel with each having its own unique radial pattern. Using cross-correlation techniques, the image analysis system identifies and tracks the relationships between the reference markers as the head moves. For example, if the head moves closer to the instrument panel, the markers appear to have moved farther apart. If the head moves farther away, the markers appear to move closer together. If the head changes orientation, the position of the markers appears to rotate.

For a 6-degree-of-freedom measurement of head position, a minimum of three reference markers must be tracked. For proper registration of head position, a minimum of two markers must be within the FOV at all times. Figure 4 shows a set of reference markers, roughly 4 cm in diameter, located within the T-37 cockpit instrument panel.

A Pentium-based PC performs the automated analyses of the video tape. Prior to analysis, a single-image frame from the video recording is grabbed and the objects of interest are identified by placing boxes around each instrument of interest. Next, the reference markers are identified and the tape is played through the system. An additional set of algorithms is then used to identify the saccadic eye movement responses, and the times of the fixation pauses. Line-of-sight measurements which fall within an instrument boundary are counted as fixations on an instrument, based on eye movement criteria defining the saccadic response and fixation pause.

Methods are presently being developed to create boundaries which more closely match the shape of the instrument or object and to resolve cases where the line of sight falls on a boundary edge. An overlay showing the scan path of one T-37 pilot radiating from the ADI can also be seen in Figure 4. usage, scanning The data provided by the program includes information on instrument sequence, and dwell time. In order to confirm accuracy of the automated system, results from the system are compared to a standard; results accomplished manually by an expert.

A comparison of results for a 2-minute time segment between the present automated system and that obtained manually by an expert are represented in Figure 5.

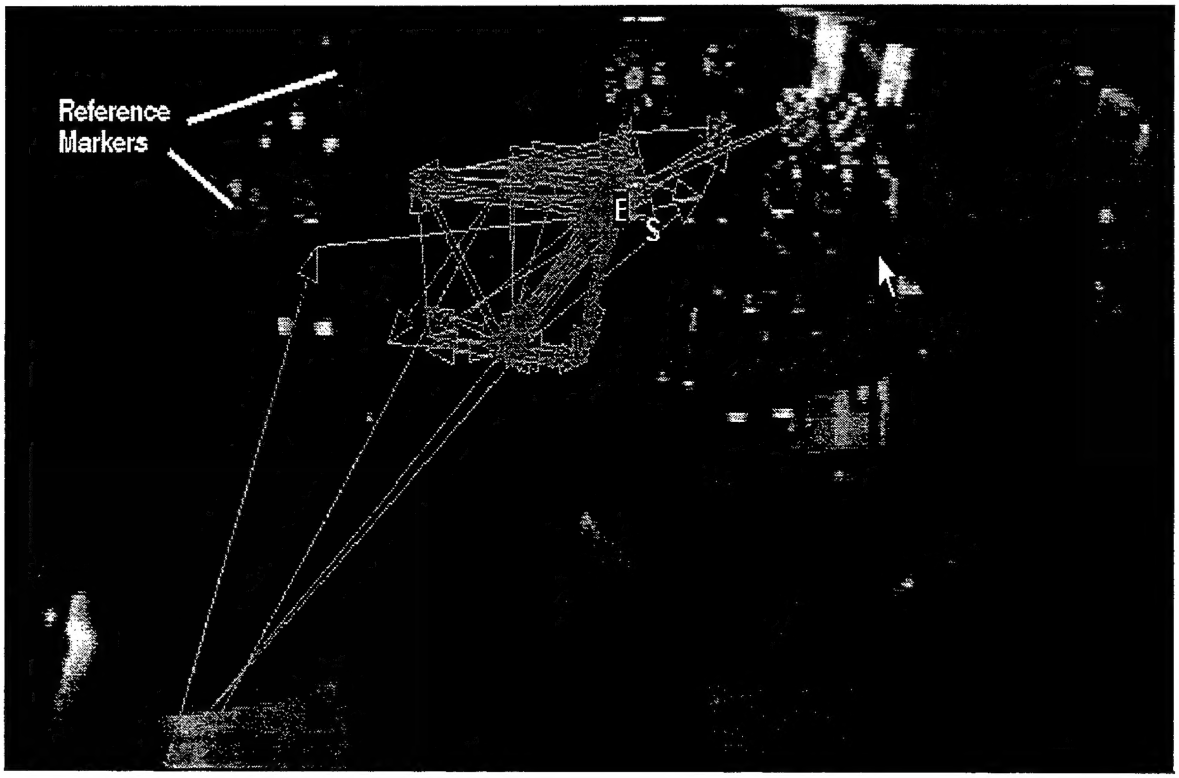

Figure 4. T-37 Pilot Scan Path During Instrument Approach (with Reference Markers)

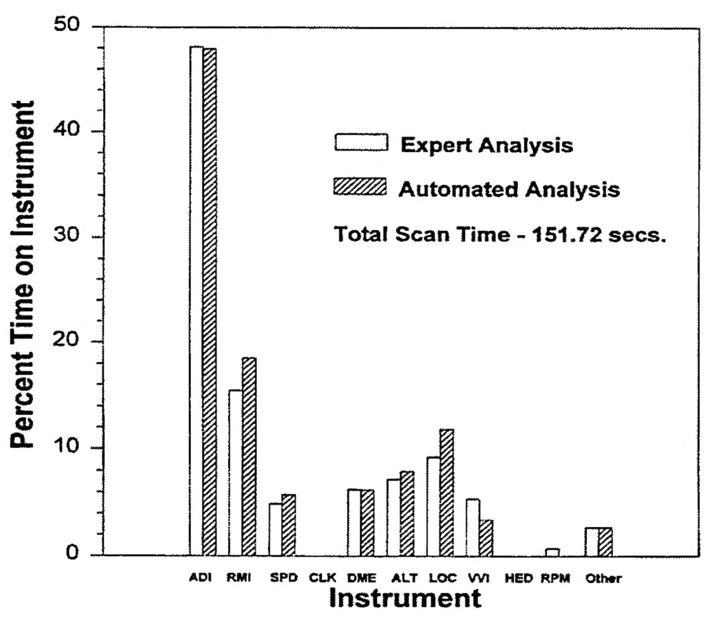

Figure 5. Comparison of Expert and Automated Analysis Showing Percent Time On Instruments In T-37 Cockpit For One Approach. The correlation coefficient (r) between expert manual and the automated analysis system is equal to 0.9983.

INITIAL APPLICATIONS AND RESULTS

Initial applications for the current study were decided upon in a joint meeting between Armstrong Laboratory, Human Systems Center (HSC), and Headquarters Air Education and Training Command (HQ AETC). Representatives from HSC worked with HQ AETC to determine deficiencies and needs that had been identified in the training environment.

The scientists from the laboratory then worked with HQ AETC to determine where the technology would have the greatest impact on training based on its capabilities. The T-37 and the F-16 were subsequently identified as areas of interest for data collection. The study was designed in two phases, the first being a "proof- of-concept" phase using IPs, and the second phase designated for working with students in an actual training environment.

During Phase I, comments from the pilots were gathered through questionnaires regarding general use and comfort and overall response to the eye tracking system. Whenever possible, these suggestions were incorporated into the system as it evolved.

The first application chosen for the portable eye tracking and analysis systems involved precision and nonprecision instrument approaches performed by T-37 IPs and student IPs in a T-37 motion base simulator at Randolph AFB, TX. Eye movement data were recorded from 16 pilots while performing three instrument approaches: an instrument landing system (ILS), a localizer (LOC), and a VHF omnidirectional range (VOR). Each session lasted approximately 50 minutes. Calibration of the eye tracking system was performed at the onset of the experiment. Setup and calibration were typically accomplished in four minutes or less. Each mission was flown twice, once without running commentary, and the second time, with the pilot providing verbal commentary describing the procedures necessary to perform the tasks at hand. We plan to compare the verbal commentary to the actual eye position data in order to determine the accuracy of the verbal description to the pilot's line-of-sight. A histogram displaying eye position data for one approach is shown in Figure 5.

The primary goal of the F-16 portion of Phase I was to obtain feedback, from pilots who are current in the weapons system, on the use of the eye-tracking system as a potential training device. After several demonstrations, we determined the best use of the system at point was in the creation of training tapes demonstrating effective scanning behavior for various complex scenarios. The scenarios identified for taping in the F-16 ACES at Luke AFB include basic fighter maneuver (BFM) setups and basic air intercepts, ending with air combat maneuvers (ACM). In the F-16 LANTIRN facility, also at Luke AFB, the scenarios included GLIB II, Terrain Following Radar (TFR) Letdown, Laser Guided Bomb (LGB) Loft, Maverick Attack, and Forward Looking Infrared (FLIR) direct attack. Setup and calibration of the eye-tracking system was accomplished in less than four minutes for most of the pilots. Eight F-16 LANTIRN IPs and F-16 IPs participated in this portion of Phase I. Training tapes generated from this phase are now being used at Luke AFB for the F-16 scenarios.

As a result of our work at both Randolph AFB and Luke AFB, several improvements were made to the portable system. Improvements include an integrated communications system, added headband comfort, reduced setup and calibration times, improved accuracy, remote VCR control capabilities, compatibility with collimated HUD imagery, and improved recording and playback quality. We are further working on schemes that will allow use of the automated analysis system with the F-16. The results of Phase I for the T-37 and F-16 studies were briefed to AETC and the applications for Phase II are being determined.

CONCLUSIONS

Portable eye tracking and companion analysis systems have been developed which allow accurate measurement of eye position. The eye tracking system combines eye position data with imagery from a head-mounted scene camera. An image-based analysis system then extracts head position based on

identification of reference markers providing head position information. A measure of head and eye position are combined to provide direction of gaze information.

The portable eye-tracking system can be employed for a variety of applications and purposes. We have demonstrated the use of the system in several scenarios and propose its use for improving training effectiveness. The portable system can also be used as a device for distinguishing strategy differences between "expert" and "novice," or less skilled individuals. Efforts are also presently underway to develop improved references for use with the automated system as well as to improve system accuracy.

The purpose of Phase II, which should be complete by the end of 1997, is to identify the effectiveness of eye tracking in training pilots to fly complex maneuvers. Through all of the tasks accomplished, from the F-15 situational awareness effort to the ongoing research effort with AETC, we have seen that eye-tracking technologies can be used to maximize training potential. The portable system that is continually being developed through the joint efforts of AL, AETC, HSC, and El Mar has been designed to maximize efficiency and accuracy, always considering the needs of the operational pilot.

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